Science and Statistics in Time Domain Astronomy and Cosmic Demographics

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Time Series in Astronomy

The nighttime sky appears constant to our naked eye ... we see an unchanging pattern of stars over our entire lives. Yet cosmic populations are incredibly dynamic, and understanding their variations is a major goal of astrophysics:

- At radio, X-ray and gamma-ray wavelengths of light, the sky is filled with pulsing, flashing, and stochastically varying objects.

- At high sensitivity (<0.01%), most stars at visible wavelengths show periodic and/or stochastic variability.

- 12% of papers in the recent astronomical literature have the words ‘variable’ or ‘light curve’ in their Abstract.
Amazing variety of temporal behaviors

- **Periodic phenomena:** orbits around stars (binary/multiple stars, exoplanets), stellar rotation (radio pulsars, solar-type stars); stellar pulsation (Cepheid & other variables, asteroseismology)

- **Stochastic phenomena:** accretion onto stars (cataclysmic variables, X-ray binaries); accretion onto black holes (X-ray binaries, active galactic nuclei); and rare processes (scintillation, blazar jets)

- **Explosive phenomena:** thermonuclear (recurrent novae, X-ray bursts); magnetic reconnection (solar/stellar flares); star death (supernovae, gamma-ray bursts)

Astronomers distinguish dozens of classes of variable objects with different time series properties
Our Sun: A complex variable star

Full disk power spectrum from 1 sec to 1 year:
- Active regions & granulation at low freq
- Millions of oscillations around 5 min

Turck-Chieze et al. 2004

Power spectrum of oscillations vs. length scale

Gizon et al. 2010
GRS 1915+050: A very nonstationary system

X-ray emission from accretion disk around a stellar mass black hole

Belloni et al. 2000
Two common difficulties in astronomical time series

Unevenly spaced observation times
Caused by diurnal & annual solar (ground-based telescopes), satellite orbits (low-Earth orbits), and telescope allocations

Heteroscedastic measurement errors
Signal-to-noise ratio different from point to point, S/N can be low or consistent with noise

These problems violate the assumptions underlying most standard time series analysis methods
Time Domain Astronomy is propelled by new wide-field multi-epoch sky surveys

These include:

- SDSS Stripe 82: 300 sq.deg, ~80 epochs, 24 mag limit (Jiang et al. 2014)
- Pan-STARRS: 30,000 sq.deg., ~week cadence, 24 mag limit (Kaiser et al. 2010)
- VVV: 560 sq.deg. in Gal plane, ~100 epochs, near-IR bands, ~10^8 stars (Saito et al. 2012)
- CRTS: 33,000 sq.deg., >10 min cadence, 20 mag limit, transients (Drake et al. 2012)
- PTF/ZTF: 30,000 sq.deg., 3 day cadence, 21 mag limit, transients (Bellm 2014)
- SkyMapper: ~20,000 sq.deg, hours-years cadence, 22 mag limit (Keller et al. 2007)
- LSST: 18,000 sq.deg., complex cadence, ~800 exposures, 4x10^{10} objects,
  15 TB & 1x10^7 alerts/night (https://confluence.lsstcorp.org/display/LKB/LSST+Key+Numbers)

The Large Synoptic Survey Telescope, now under construction in Chile, is the U.S. national telescope project for the 2020s
Birth of gravitational wave astronomy

**Laser Interferometric Gravitational Observatory**
An unusual multiple-site telescope to measure tiny ripples in space-time from rapidly changing strong gravitational systems such as inspiralling black holes

**GW150914:** After decades of frustration, a superb unequivocal GW signal was seen on 14 Sept 2015. Many other signals are being sought, most close to the noise level.

Abbott et al. 2016
Statistical challenges for SAMSI consideration: established methods

- Procedures for characterizing unevenly spaced data have been heavily used for decades in astronomy: Edelson-Krolik Discrete Correlation Function (1988), structure function (1985), Stellingwerf’s (1977) phase dispersion minimization & other non-Fourier periodograms, Lomb-Scargle (1982) Fourier periodogram. What are their mathematical properties?

- Parametric autoregressive (ARMA-type) modeling is very common outside astronomy for aperiodic stochastic variations (e.g. accretion systems, stellar magnetic activity). To what degree can they be adapted to unevenly spaced astronomical data?
Statistical challenges for SAMSI consideration: new problems

• Characterize and classify large ensembles ($10^8$-$10^{10}$) of irregularly spaced lightcurves from multi-epoch visible light wide-field surveys and classify them into dozens of classes of variable objects, culminating in U.S. 2020s LSST project

• Classify and model supernova Type Ia lightcurves with noisy, irregularly sampled lightcurves

• Signal detection from multi-telescope radio interferometers involving rotating neutron stars: nanohertz gravitational wave detection, rotating radio transients (RRATs), fast radio bursts (FRBs)

• Weak detection of periodic signals in red noise for exoplanet detection, radial velocity & photometric transit surveys

• High-dimensional model selection for multi-planet systems